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Effect of scattering noise on the data fidelity of holograms recorded

in photorefractive crystals

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ABSTRACT

In this paper a method is proposed to investigate how the scattering noise of photorefractive crystals influences the quality of an input data page in holographic storage. By illuminating the crystal under investigation with an intense coherent light beam, and measuring the signal-to-noise ratio (SNR) of an image formed through the crystal before and after the exposure, the loss of SNR provides a good assessment for the suitability of the crystal for data storage. A variety of doped lithium niobate crystals were investigated. The results show that the intensity of fanning light increases with increase of the doping concentration, but there is no strict correlation between the fanning strength and the fidelity degradation. Owing to the low noise and high data fidelity, iron-and- zinc co-doped lithium niobate crystal is a potential material for high-density holographic data storage.

INTRODUCTION

Holographic data storage is a topic of widespread research interest [1-3]. The ability to store multiple holograms within a small volume of thick materials, such as photorefractive crystals, and to retrieve data pages with thousands of bits in parallel provides an attractive combination of density and speed. However, the various noises, such as the constant noise floor, cross talk between multiplexed holograms and the scattering noise, existing in the holographic systems reduce the capacity far from the ideal value determined by the diffraction limitation. So this is a major obstruction to the practice of volume holographic storage. In order to achieve the high capacity of holographic storage, data retrieved from holograms with high signal-to-noise ratio (SNR), and hence, low bit-error-rate is essential. It is demonstrated that the noise arising from holographic multiplexing can be far less significant than the system noise including the scattering noise arising from the recording medium. [4, 5] In this paper, we investigate the influence of scattering noise on image fidelity, with special attention paid to the influence of the scattering noise in photorefractive lithium niobate crystals on the quality of input data pages before the hologram formation.

THEORY

Photorefractive light-induced scattering noise is usually called "beam fanning", in which a collimated beam of light is scattered into a broad fan as it propagates through a high-gain

crystal. [6] It is proposed that the fan originates from the scattering of defects in the crystal, which then become amplified by the two-beam coupling process. In doped or co-doped LiNbO₃ crystals, the source of the fanning noise comes from the scattering on imperfections in the crystal, and the scattered light interferes with the initial beam, creating a phase grating in the crystal. Both the initial beam and the scattered beam are automatically Bragg matched to this grating, and self-diffraction occurs. Beam fanning can be a strong effect, removing almost all of the light from the incident beam in the worst case.

The mechanism of fanning effect has been widely studied (see, for example, Ref. [7]). The phenomenon is somewhat complicated, and the strength of the effect depends on various factors such as the crystal orientation, size and intensity of the incident light, and material parameters, etc. The following quantities can be used for measuring the fanning effect: (1) the power of scattered light, P_f, which forms a pattern in the observation screen separated from the initial light spot; (2) the scattering ratio R of the total fanning noise intensity to the total incident light intensity, [8] given as

$$R = \frac{I_0 - I_f}{I_0} \tag{1}$$

where I_0 is the initial intensity of the incident light, and I_f is the final intensity of the incident light after the scattering being saturated. The larger P_f and/or R are, the more serious the scattering is.

The noise grating formed in the crystal through beam fanning can be read out by any beam that is partially Bragg-matched to this noise grating, resulting in some noise in the output beam. In the case of hologram multiplexing, a large number of holographic recordings causes the fanning process to a given hologram, that is, the scattering noise deteriorates the input signal (image), and hence, the quality of the retrieved image.

The fidelity of a holographic data page (image) is normally specified by the signal-to-noise ratio (SNR) that is defined as

$$SNR = \frac{I_1 - I_0}{\sigma_1 - \sigma_0} \tag{2}$$

where I_1 and I_0 is the average value of bright and dark pixels, respectively, σ_1 and σ_0 is the corresponding standard variation. In this paper we use the loss of signal-to-noise ratio (*LSNR*) for characterizing the degradation of image fidelity due to the scattering noise,

$$LSNR = 10 \times \log\left(\frac{SNR_0}{SNR_f}\right), \tag{3}$$

where SNR_0 is the SNR of the original image that was obtained through a "clean" crystal (all gratings previously recorded in the crystal are thermally erased) inserted in a noisy optical imaging system, whereas SNR_f is the SNR of the same image obtained through the same system after the scattering in the crystal reaches saturation. The lower the *LSNR* of a material, the better the image fidelity it may provide.

EXPERIMENT

We conducted experiments to investigate the effect of scattering noise on the data fidelity of holograms recorded in photorefractive crystals using a traditional Fourier transform holography system. An intense coherent beam with a diameter of 3 mm (total power 38mW for transmission geometry and 80mW otherwise), which acts as the reference beam in holographic recording, illuminated the crystal until the scattering reached saturation. The illumination time T_f depends on the crystal samples. The power of the scattered light P_f and/or the scattering ratio R was measured. For measuring P_f the full aperture of the detector (with an area of about 1 cm^2) was used, while for measuring R the detector was 3-mm apertured. The SNR_0 and SNR_f of an image, formed directly through the crystal inserted near the spectrum plane, were also measured before and after the illumination of the crystal by the reference beam. A relation between $LSNR$ and P_f (or R) was expected to reveal the influence of scattering noise on the image fidelity. By using this method, we tested a variety of lithium niobate crystals doped or co-doped with different dopants and doping concentrations, and with different treatment after crystal growth. The recording configurations under investigation included transmission, reflection, and 90-degree geometry.

RESULTS

The influence of scattering on the image fidelity is highly dependent on the crystal orientation. For a given sample and configuration, we made measurements for two crystal orientations anti-parallel to each other. Shown in Table 1-3 are results for the worse case. The values of scattered power were measured only for reflection geometry.

Table I: Influence of fanning noise on the image fidelity for Fe: LiNbO3 crystals with different doping concentration and treatment. Recording geometry: reflection

Doping Concentration and Treatment	Crystal ID	T_f(min)	P_f (µW)	R	LSNR (dB)
Fe: 0.10%, As grown	A2	20	560	0.76	0.09
Fe: 0.01%, As grown	A	14	116	0.94	0.60
Fe: 0.004%, As grown	D	12	0	NA	0.04
Fe: 0.06%, Oxidized for 4 hours	6#	14	322	0.9	0.18
Fe: 0.06%, Oxidized for 24 hours	7#	20	180	0.9	1.43

Table II: Influence of fanning noise on the image fidelity for different recording geometry

Recording Geometry	Crystal ID	Dopant	T_f(min)	P_f (µW)	R	LSNR (dB)
Reflection	8#	Fe: 0.08%	16	220	0.93	0.13
Transmission	9#	Fe: 0.08%	0.6	NA	0.94	3.47
90-degree	S4	Fe: 0.03%	10	NA	0.95	0.09
	S3	Fe: 0.03%, Ce: 0.1%	13	NA	0.96	0.36

Table III: Influence of fanning noise on the image fidelity for samples with different dopants

Dopant	Crystal ID	Recording Geometry	T_f(min)	P_f (μW)	R	$LSNR$ (dB)
Fe: 0.08%, Mn: 0.05%	2B		29	199	NA	0.81
Fe: 0.03%, Ce: 0.05%	Ce2	Reflection	28	1	0.84	0.36
Fe: 0.08%	8#		16	220	0.93	0.13
Fe: 0.03%, Zn: 6mol%	2#	Transmission	50	NA	0.67	0.03

DISCUSSION

It is obvious from Table 1 that heavy doping of iron in $LiNbO_3$ causes serious fanning which degrades the image quality. This is because the dopants act as additional scattering centers. Strong oxidation makes situation even worse. Since the oxidization process increases the concentration of Fe^{3+}, this suggests that Fe^{3+} irons contribute more to the scattering than Fe^{2+}. Shown in Fig. 1(a) is the image formed through the crystal 9# before it was exposed to the intense reference beam. The image quality is fairly good. In contrast, the image formed through the same crystal after coherent illumination for only 36 seconds was entirely destroyed as shown in Fig. 1(b). From Table 2 one can see that the 90° geometry is least subject to the influence of scattering noise, while the transmission geometry is most. Table 3 shows clearly that an additional dopant of Mn or Ce co-doped with Fe in $LiNbO_3$ crystals causes normally more serious scattering. However, when the additional dopant is Zn, the situation reversed. Doping of a certain amount of Zn as an anti-photorefraction dopand in $LiNbO_3$ effectively reduced the scattering noise effect.

(a)   (b)

Fig. 1 Image formed through crystal 9# (a) before and (b) after the crystal being exposed to an intense coherent beam for 36 seconds ($LSNR$=3.47).

<div align="center">(a)   (b)</div>
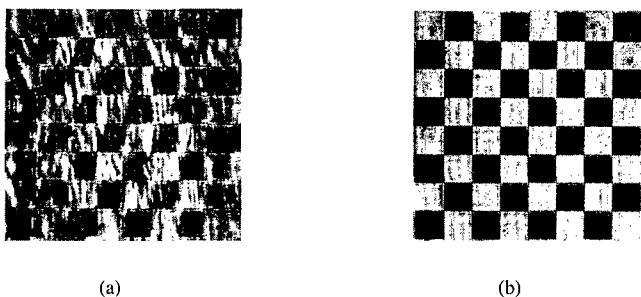
Fig.2 Image retrieved from a hologram stored in (a) crystal 9# with 7 minutes of coherent illumination before storage, and (b) crystal 2# with 50 minutes of coherent illumination before storage.

Comparing the far-right 3 columns in Table 1 through Table 3, we can see that there is no strict correlation between the decrease of SNR of an image and the fanning effect measured as P_f or R. Thus, we cannot determine if a crystal is suitable for holographic storage according only to the amount of measured scattering. On the other hand, the decrease of SNR, $LSNR$, does describe the image fidelity of a hologram. Figure 2 illustrates that holograms of data pages stored in crystal sample 2#, chosen by using the above method, reached satisfactory data fidelity.

CONCLUSIONS

This research investigated how the scattering noise influences the quality of an input data page in holographic storage. The experimental results show that among the three recording configurations, 90° geometry is least subjected to light-induced image-fidelity degradation. The intensity of fanning light increases with increase of the doping concentration, but there is no strict correlation between the fanning strength and the fidelity degradation. Therefore, one should not determine whether or not a crystal is suitable for high-fidelity holographic storage only according to its fanning power. The loss of SNR introduced in our work provides a better assessment for the suitability of the crystal for data storage. Owing to the low noise and high data fidelity, iron-and- zinc co-doped lithium niobate crystals are potential materials for high-density holographic storage.

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